Polariton Condensation

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Windsor 2010

Collaborators

Theory

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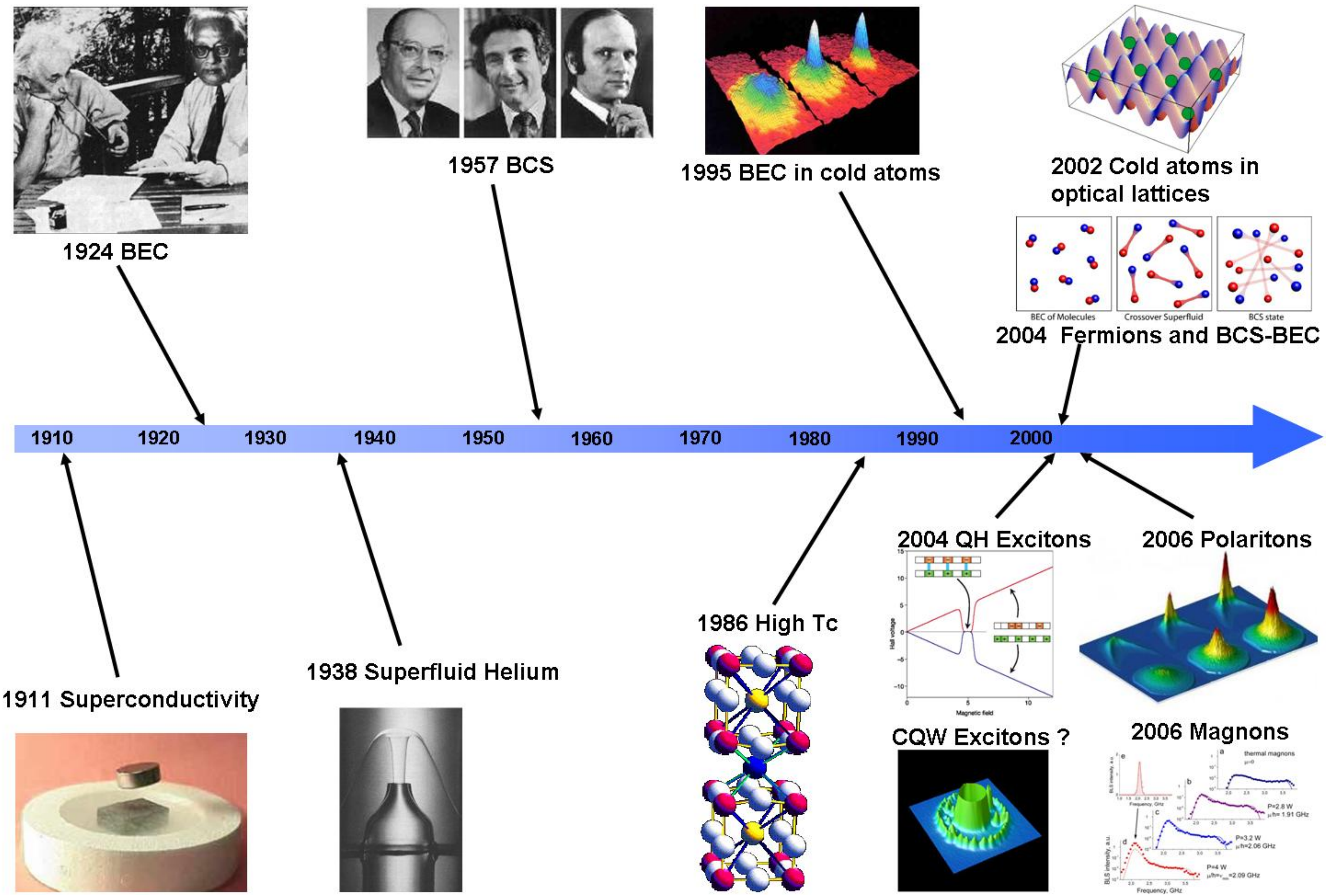
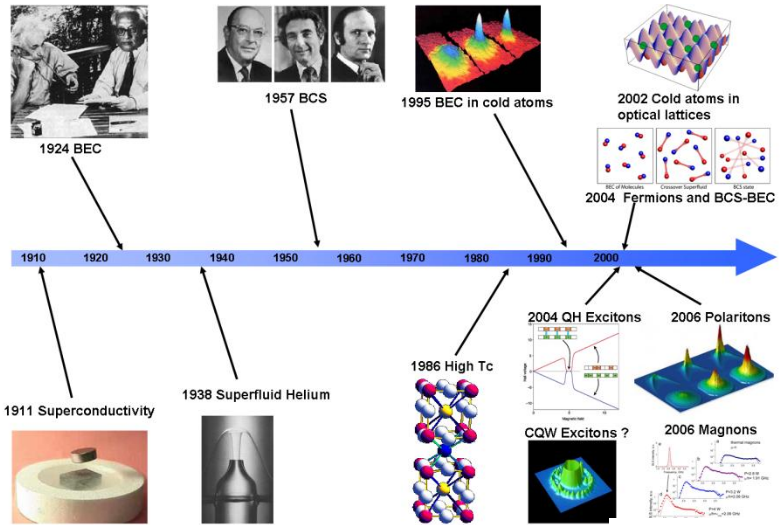
Funding from

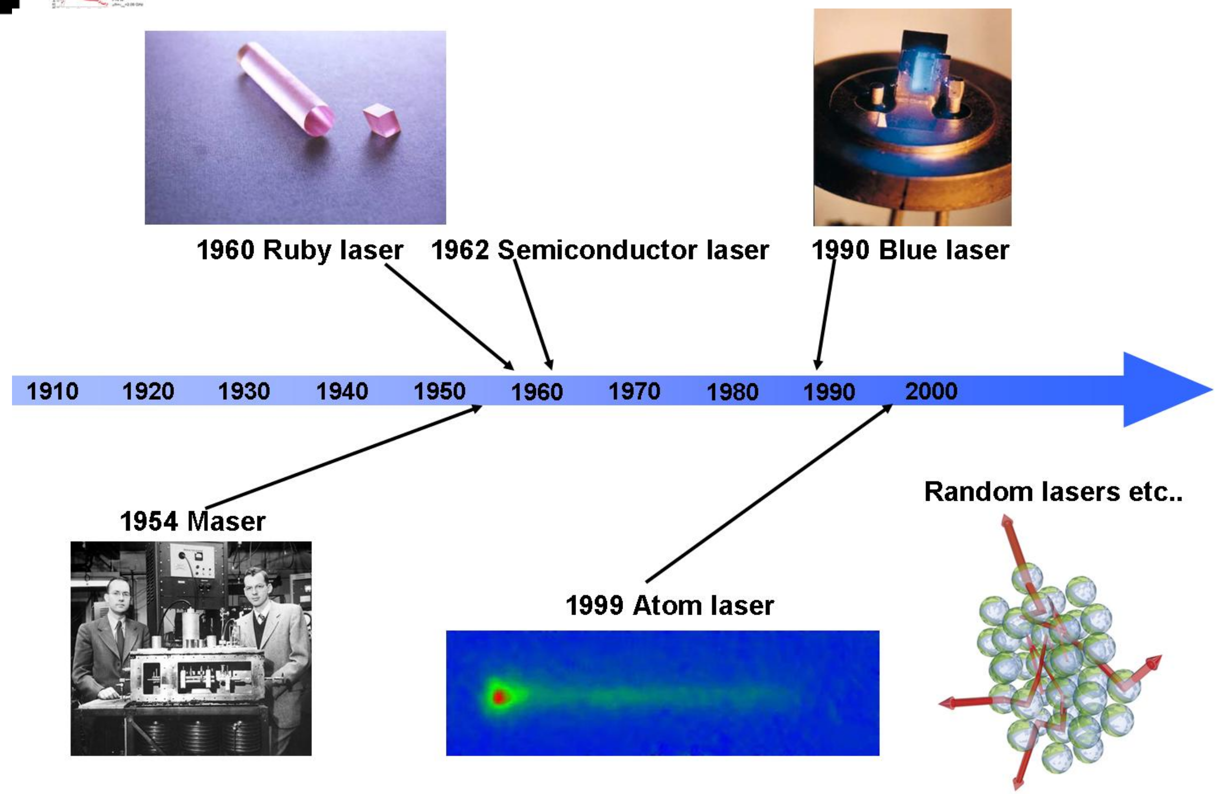
EPSRC Engineering and Physical Sciences Research Council

Macroscopic Quantum Coherence



Macroscopic Quantum Coherence





Outline

✓ Lecture 1:
Introduction: BEC-BCS, excitons, polaritons, experiments

✓ Lecture 2:

Part1: Quantum condensation in non-equilibrium dissipative systems

- non-equilibrium field theory
- probes of dissipative BEC

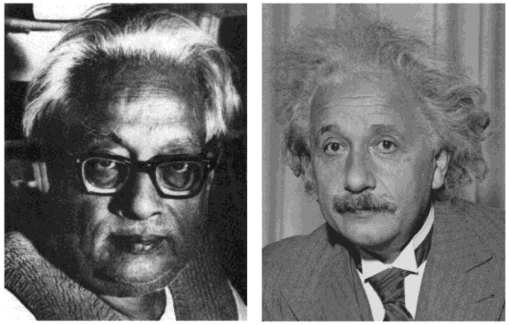
Part2: Superfluid properties

Bose-Einstein Condensation

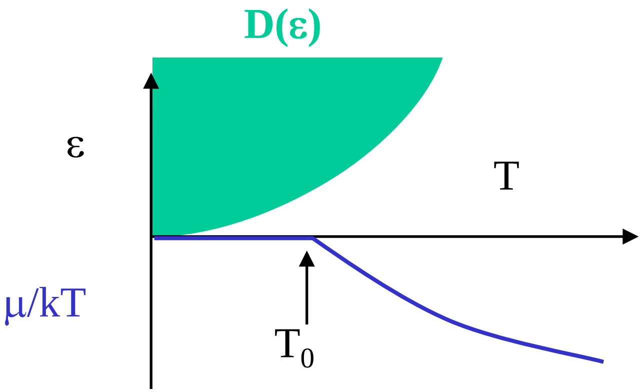
BEC = macroscopic occupation of a single quantum (ground) state of massive particles at thermal equilibrium

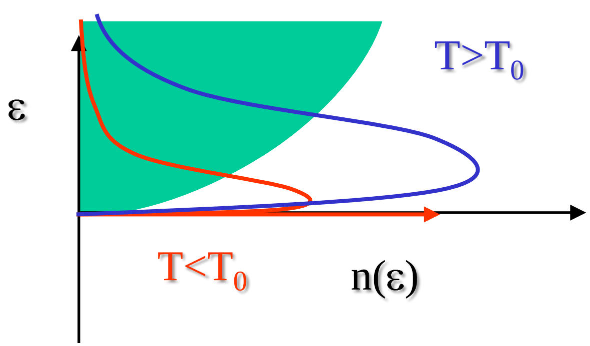
$$N = \int d\epsilon \frac{D(\epsilon)}{e^{\beta(\epsilon-\mu)} - 1}$$

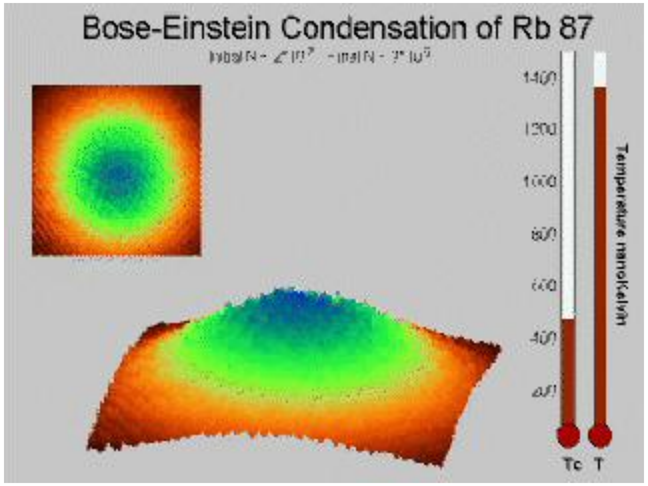
Bose-Einstein condensation * 1925



Satyendra Nath Bose Albert Einstein







Bose-Einstein Condensation and Interactions

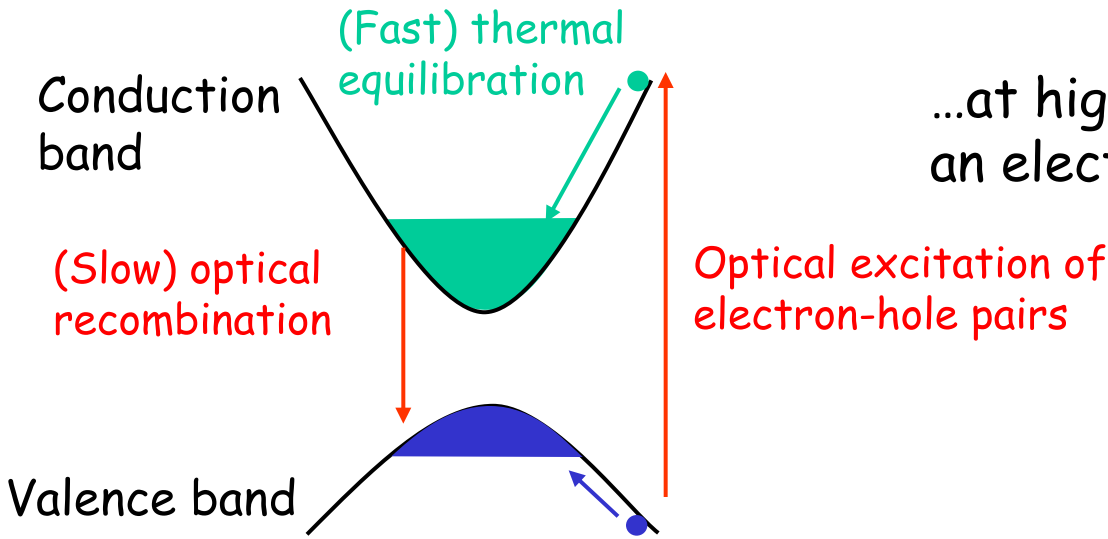
Macroscopic Phase Coherence

= macroscopic wave function which arises from interactions $\psi e^{i\phi}$

Superfluidity - linear sound mode with dispersion and hence a superfluid stiffness c $\omega = cq$

Excitons in Semiconductors

✓ Electron-hole pairs created by optical excitations …

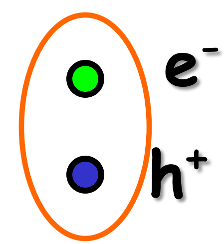


…at high density form an electron-hole plasma

…at low densities can bind to form excitons (analogue of hydrogen)

✓ Binding is weak and radius is large

e.g. in GaAs ($m^* \sim 0.1\ m_e$, $\epsilon = 13$)
Binding energy = 5 meV (13.6 eV for Hydrogen)
Bohr radius = 7 nm (0.05 nm for Hydrogen)



i.e. large compared to inter-atomic distances

Exciton Condensation

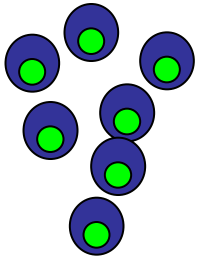
✓ At low densities ($n_{\rm exc} a_0^d \ll 1$) tightly bound excitons

- capacity to undergo **Bose-Einstein condensation**[1]

Exciton mass is small, critical temperature

$$k_{\rm B} T_{\rm c}^{3D} \sim \frac{n_{\rm exc}^{2/3} \hbar^2}{m_{\rm exc}}$$

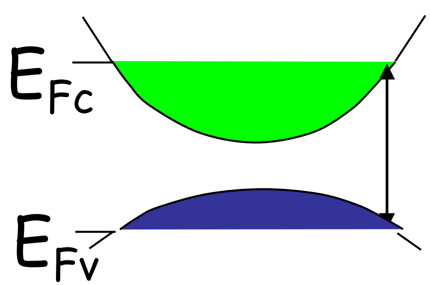
is large (ca. 1K at realistic densities)



BEC-like phase of excitons

✓ At high densities ($n_{\rm exc} a_0^d \sim 1$) electrons and holes unbind

- capacity to `condense' into **excitonic insulator** phase[2] (two-component **BCS**)



BCS-like instability of Fermi surfaces

[1]Keldysh and Kozlov '68
[2]Keldysh and Kopaev '64

BCS-BEC crossover

Keldysh and Kopaev '64
Eagles '69, Leggett '80

Same $|\Psi\rangle$ can describe BEC of bosons at low density\strong interaction and BCS state of fermions at high density\weak interactions.

$$|\Psi_{\rm BCS}\rangle = \prod_k \left[u_k + v_k a^\dagger_{k\uparrow} a^\dagger_{-k\downarrow}\right] |{\rm vac}\rangle \qquad v_k/u_k = \phi_k$$

Pair wave-function

Why ? It is a coherent state $|\Psi\rangle = e^{\sum_k \phi_k a^\dagger_{k\uparrow} a^\dagger_{-k\downarrow}} |{\rm vac}\rangle$

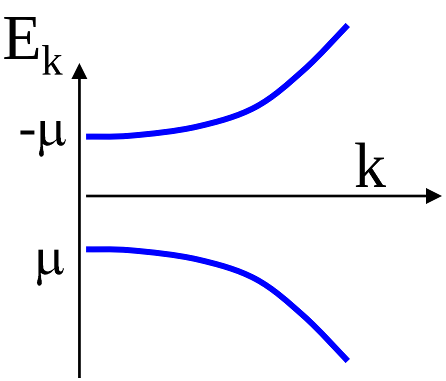
Gap equation

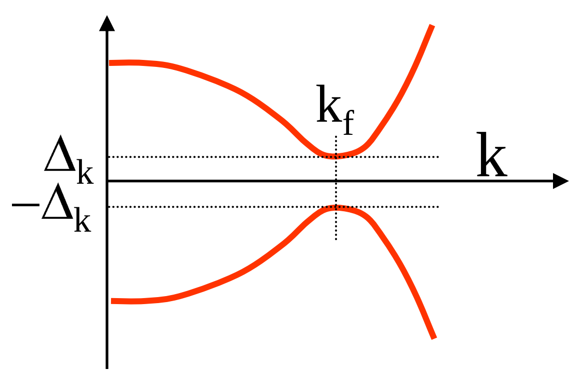
$$\Delta_k = \sum_{k'} \frac{1}{2E_{k'}} V_{kk'} \Delta_{k'}$$

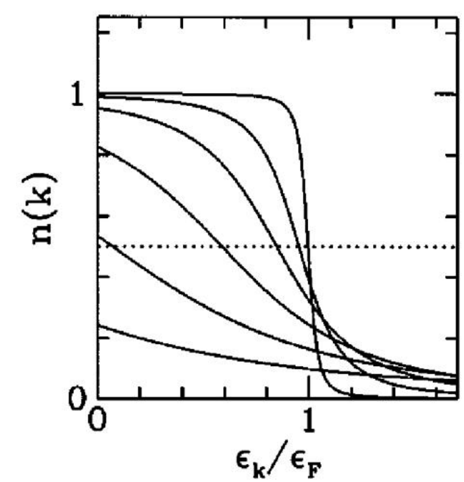
Density equation

$$N = \sum_k \left(1 - \frac{\epsilon_k}{E_k}\right)$$

$$E_k = \sqrt{(\epsilon_k - \mu)^2 + |\Delta_k|^2} \qquad E_{\rm min} = \begin{cases} \sqrt{|\mu|^2 + |\Delta|^2}, & \mu < 0 \\ |\Delta|, & \mu > 0 \end{cases}$$





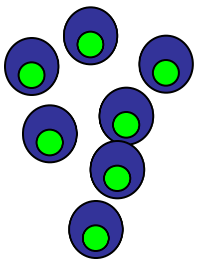


Randeria

Mean-field Theory of Exciton Condensation

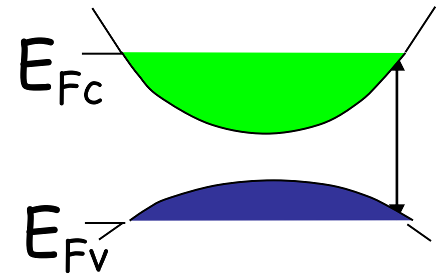
Keldysh and Kopaev '64

$$\hat{H} = \sum_k \epsilon_k \left(a^\dagger_{\mathrm{c}k} a_{\mathrm{c}k} - a^\dagger_{\mathrm{v}k} a_{\mathrm{v}k} \right) + \hat{V}_{\mathrm{Coulomb}}$$



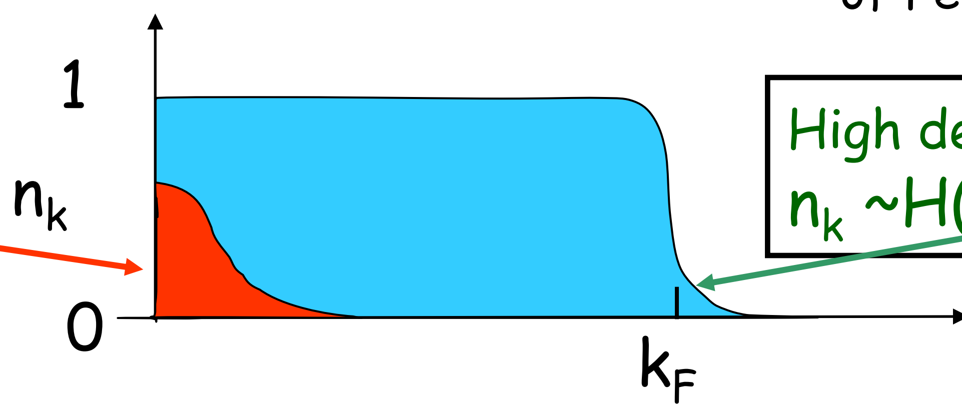
BEC-like phase of excitons

$$|\Psi\rangle = \prod_k \left[u_k + v_k a^\dagger_{\mathrm{c}k} a_{\mathrm{v}k} \right] |0\rangle$$



BCS-like instability of Fermi surfaces

Low density
$n_k \sim n^{1/2} f_k$



High density
$n_k \sim H(k_f - k)$

BCS-BEC crossover driven by change in excitonic density

Experiments towards BEC of Excitons

- ✓ Early attempts
  - Cu_2O dipole-forbidden excitons
  - Biexcitons in CuCl

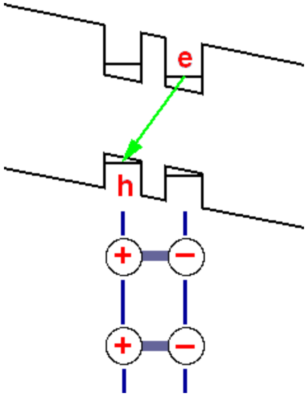
Obstacle: Auger recombination

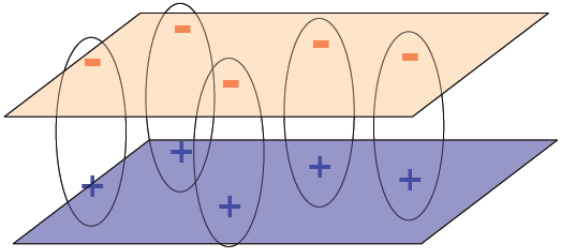
- ✓ New promising candidates
  - Indirect excitons in coupled quantum wells

Butov et al PRL (2001), Nature (2002), Snoke et al, Nature (2002);

Electrons

Holes





- bias across QWs leads to long-lived spatially indirect excitons

- coherence of excitons would show in photoluminescence

Experiments towards BEC of Excitons

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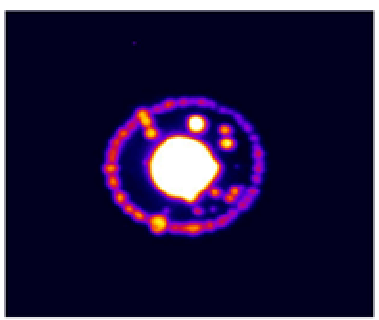
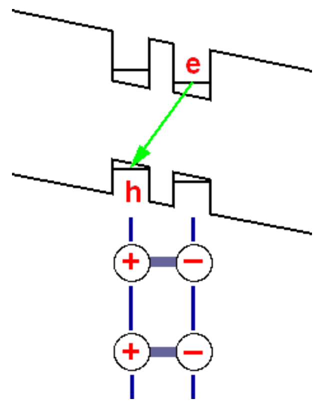
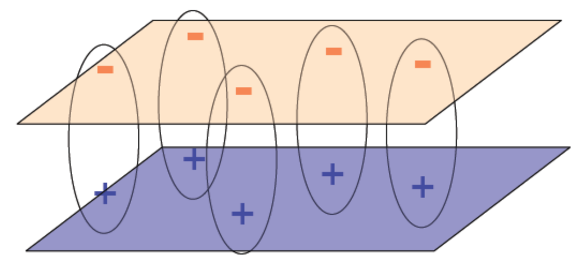






- bias across QWs leads to long-lived spatially indirect excitons

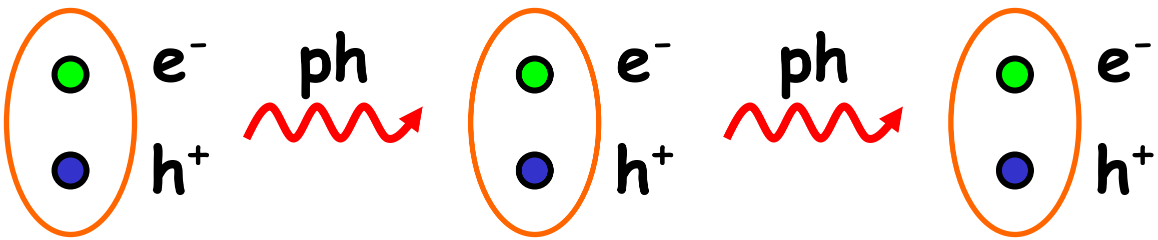
- coherence of excitons would show in photoluminescence

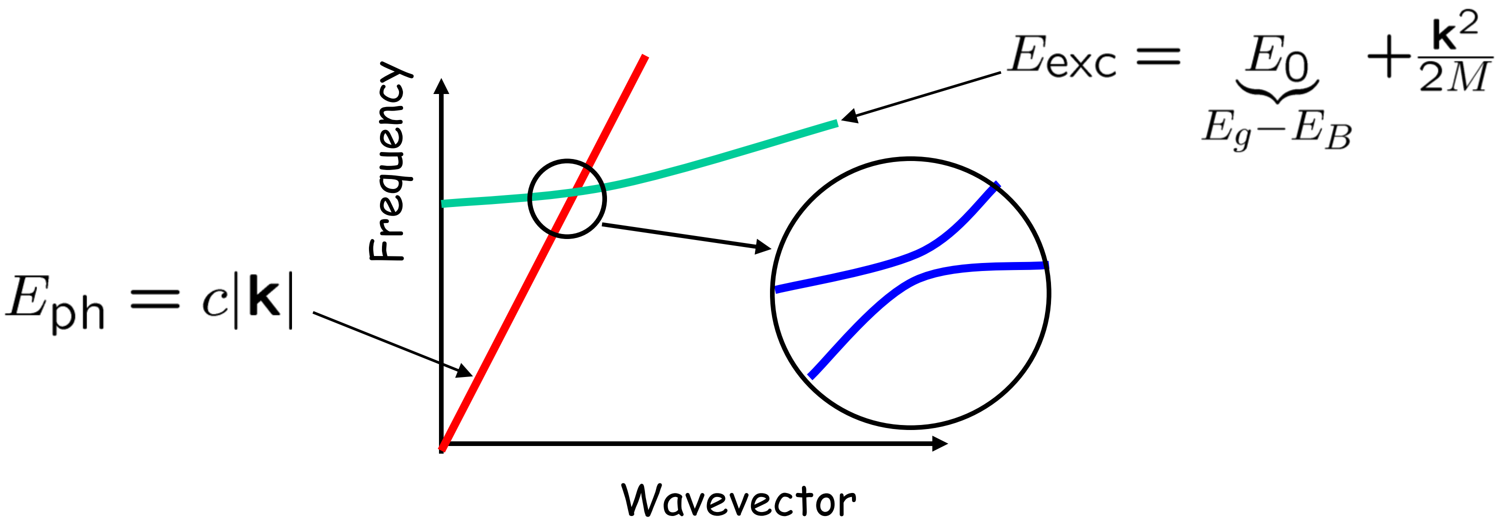
- fragmentation pattern observed requires non-linear (stimulated) process[1]

[1] L. S. Levitov et al, Phys. Rev. Lett. **94**, 176404 (2005)

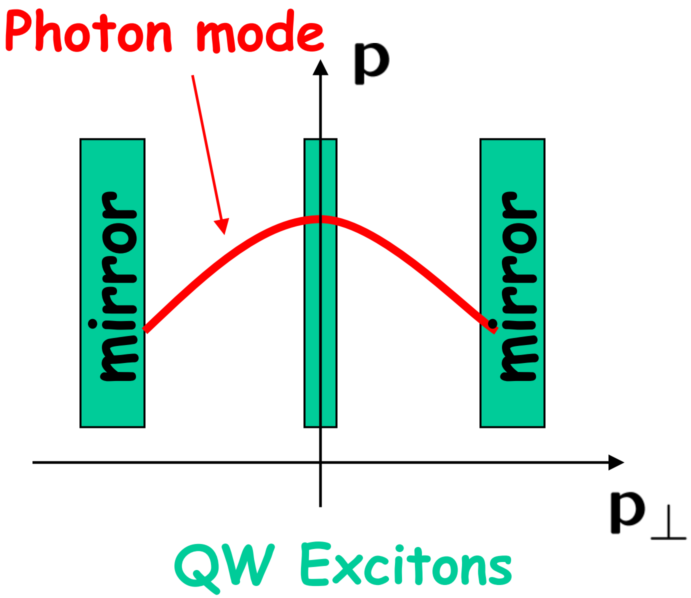
Polaritons

- ✓ Strong exciton-photon interaction - polariton
- ✓ Polaritons [J.J. Hopfield *Phys Rev* **112**, 1555 (1958)]
  = mixed modes of excitonic polarisation and light



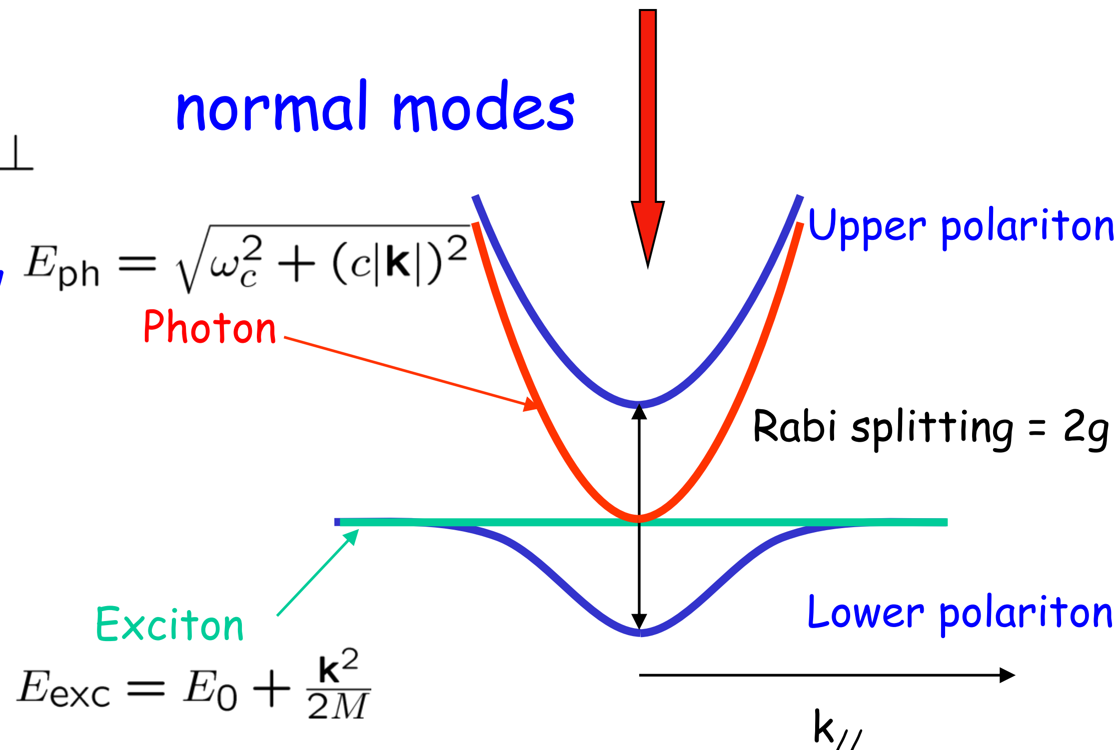


Microcavity Polaritons



dipole coupling

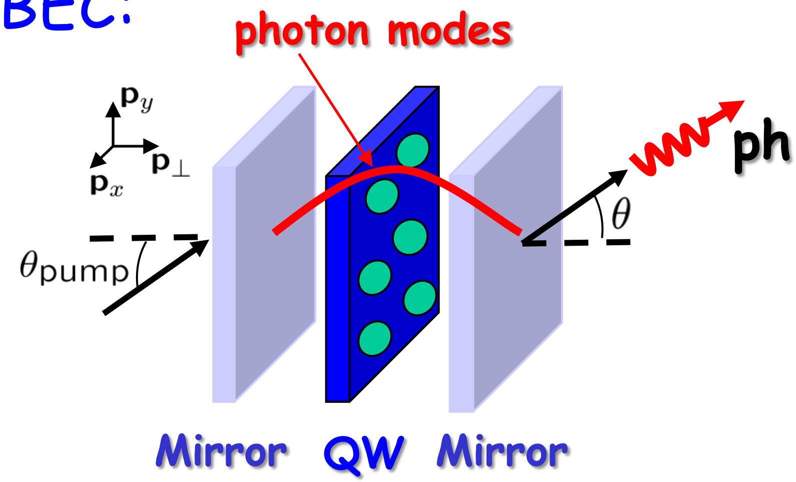
$$\begin{pmatrix} E_{\text{exc}} & g \\ g & E_{\text{ph}} \end{pmatrix}$$

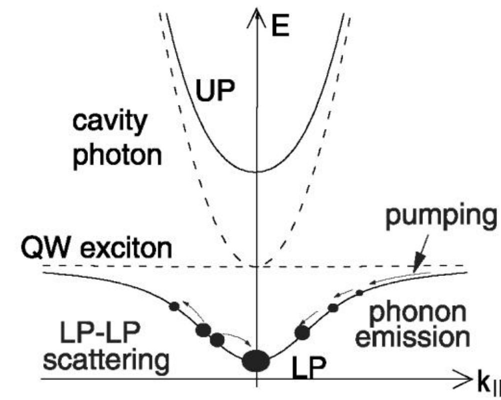


- ✓ Optical microcavities allow
  - to confine the optical modes
  - to control the interactions with the electronic polarisation
- ✓ Polariton mass = 10^{-9} mass of Rubidium atom
- ✓ Experimentally realised: C. Weisbuch et al. *PRL* **69**, 3314 (1992)

Early Experiments - towards BEC

✓ Towards BEC:





- Nonlinear growth of emission without bleaching of polariton line much below the population inversion not a photon laser!

Pau et al, *PRA* **54**, 1789 (1996); Dang et al. *PRL* **81**, 3920 (1998); Senellart et al, *PRL* **82**, 1233 (1999), Savvidis et al. PRL 84 1547 (2000), Stevenson et al. PRL 85 3680 (2000)

- Decrease of the second order coherence function $g^{(2)}$ coherence?

- Narrowing of the N(θ) photon distribution spatial coherence?

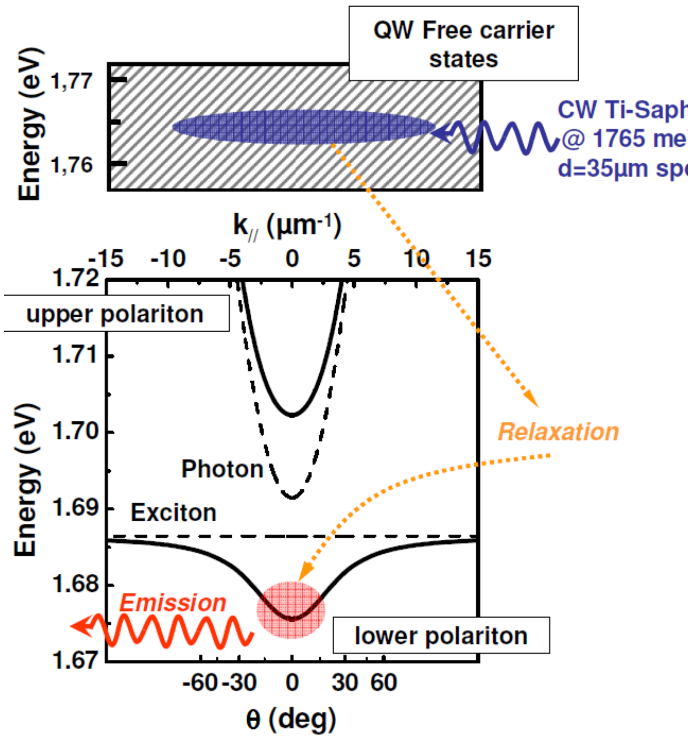
Deng et al. *Science* **298** 199 (2002), *PNAS* **100** 15318 (2003)

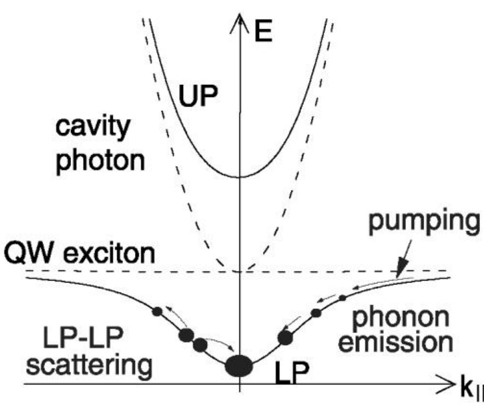
- Interference fringes

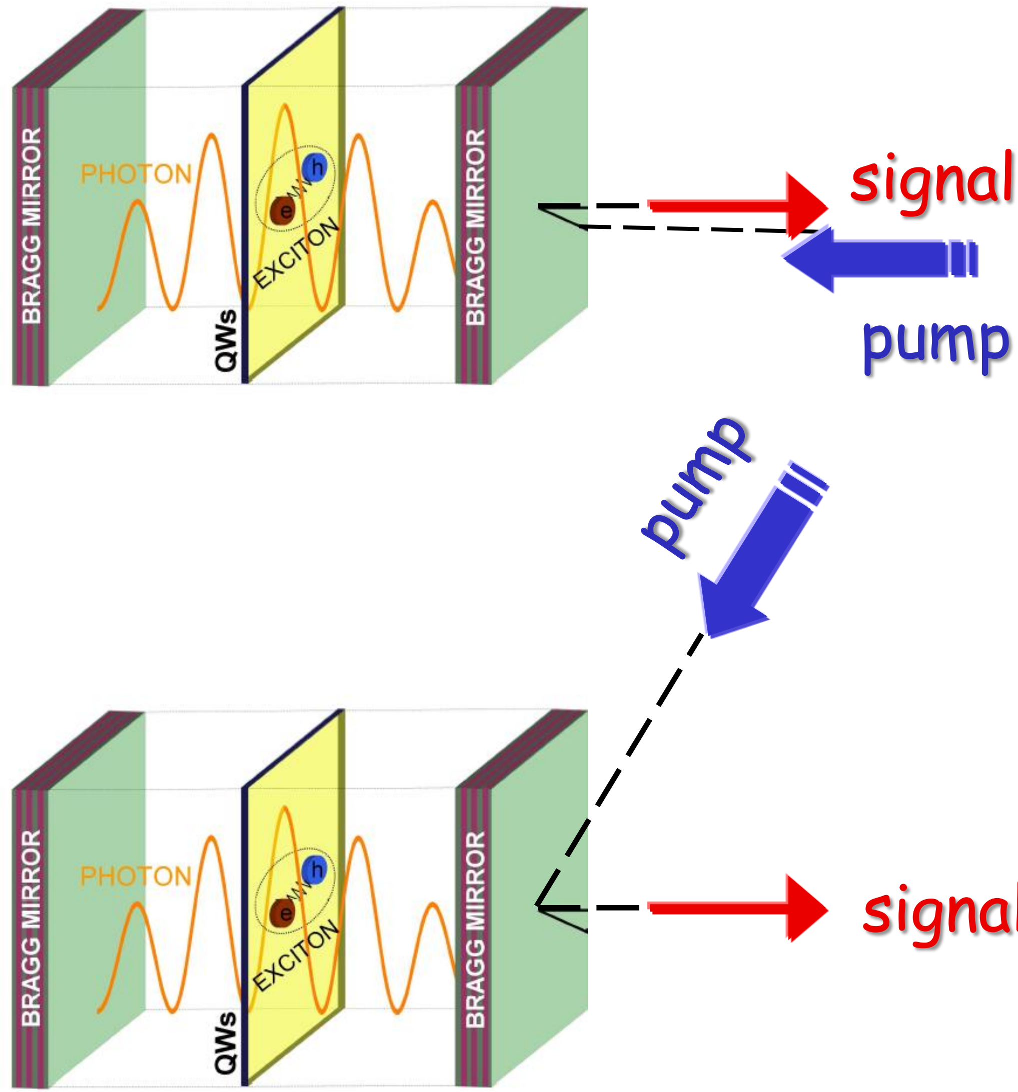
Richard et al. *Phys. Rev. Lett.* **94**, 187401 (2005)

Different Pumping Schemes

Incoherent

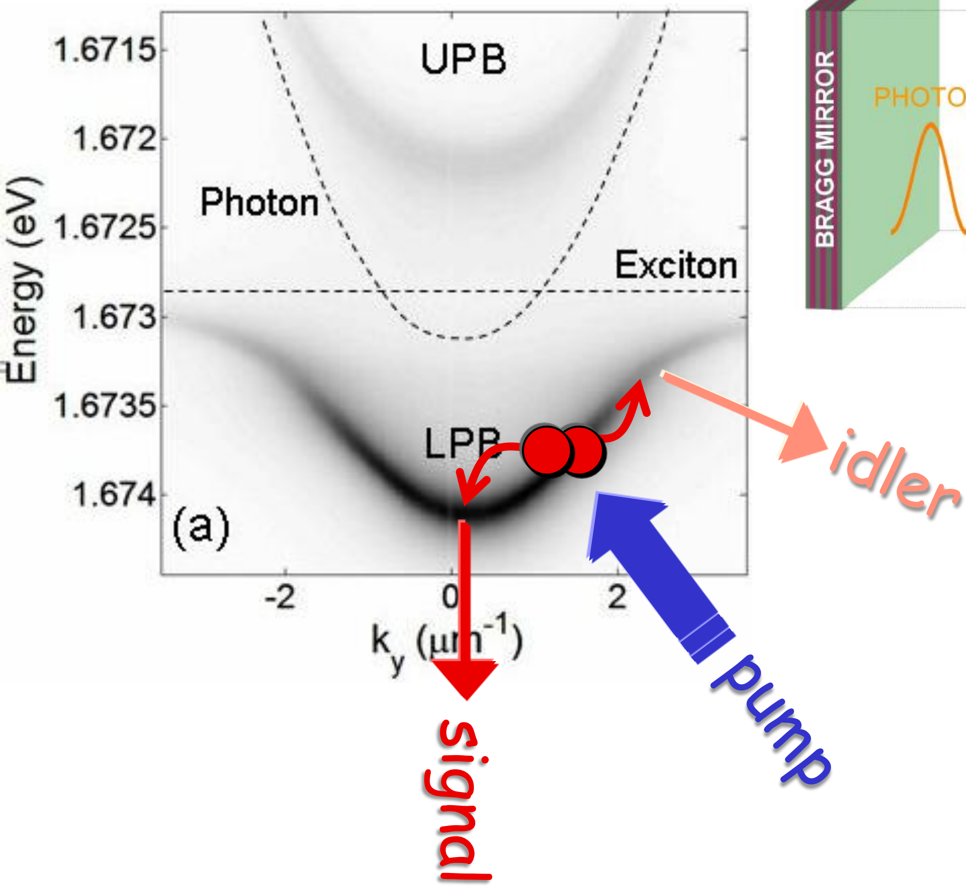


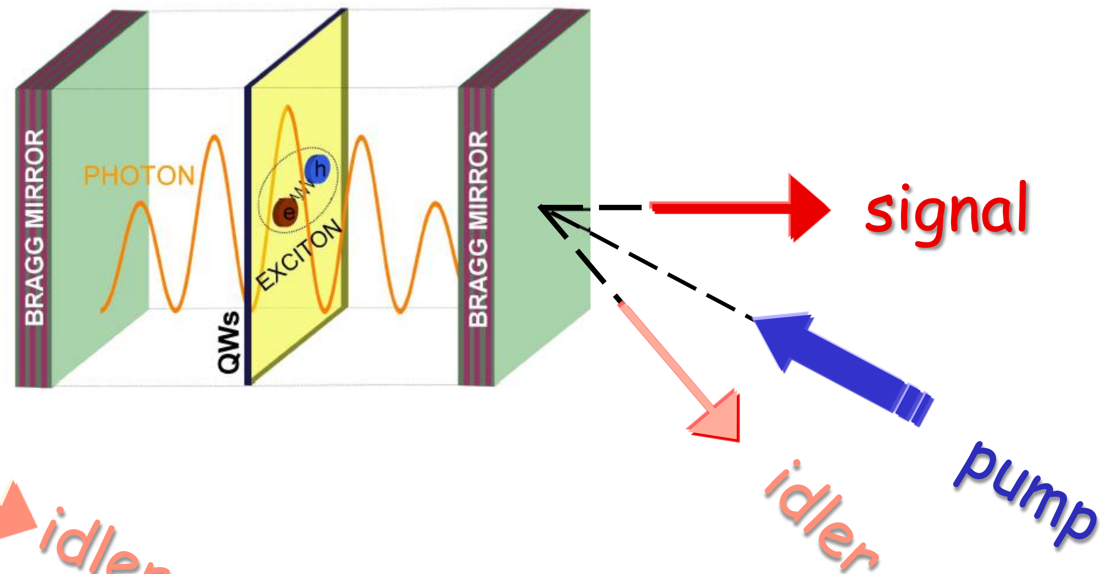




Different Pumping Schemes

Parametric

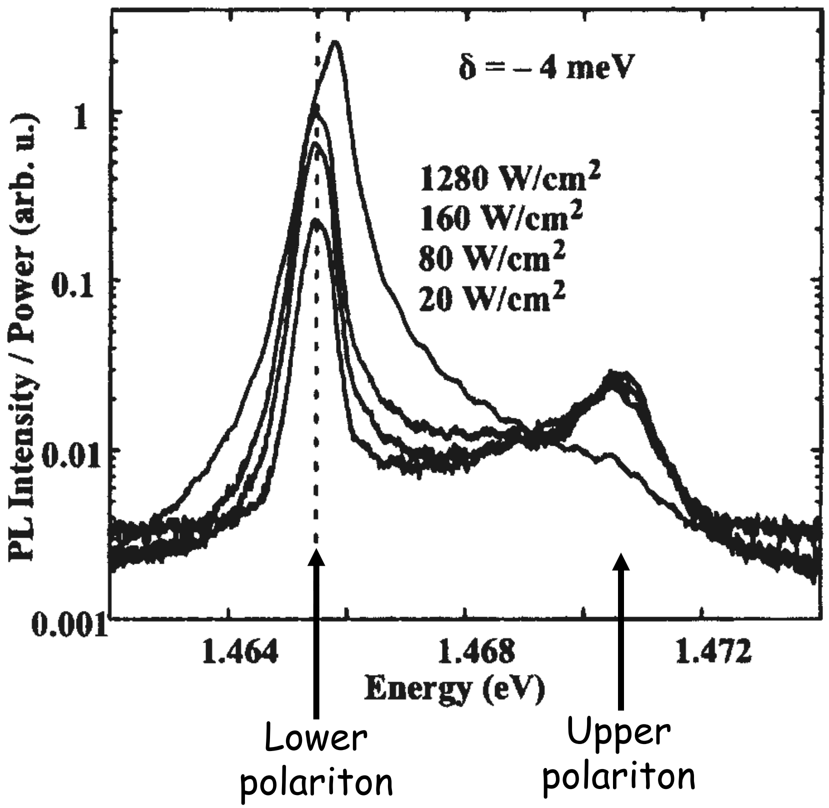




Bosonic Stimulation

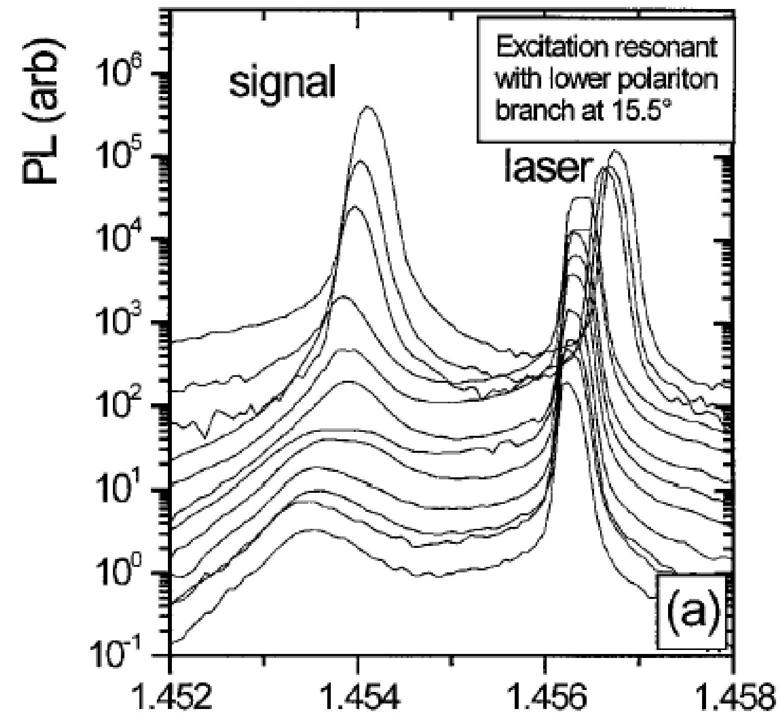
Incoherent

PL normalised to pump intensity



Senellart & Bloch, PRL 82, 1233 (1999)

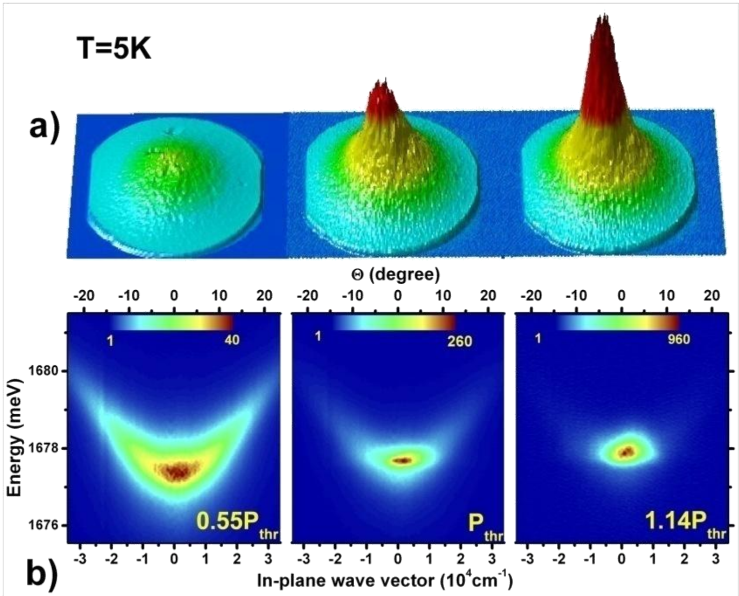
Parametric

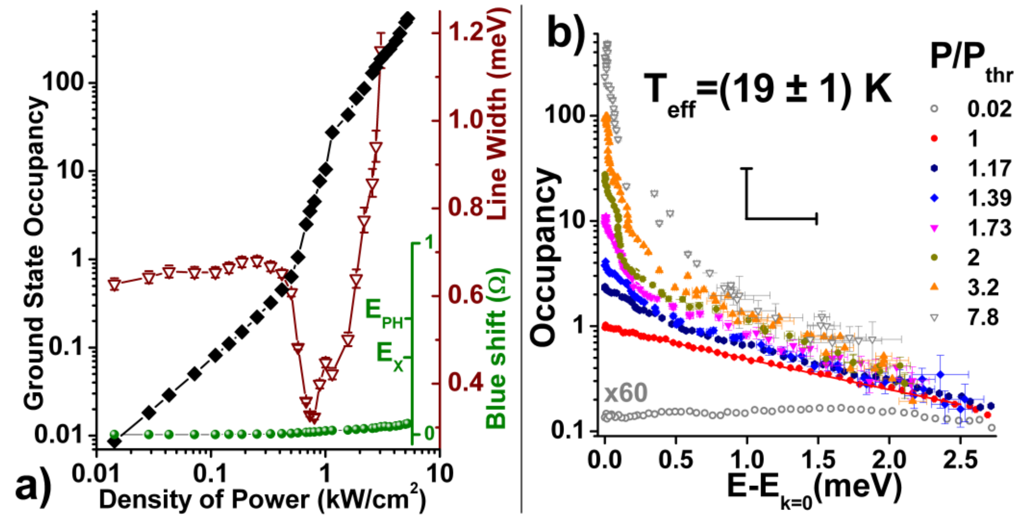


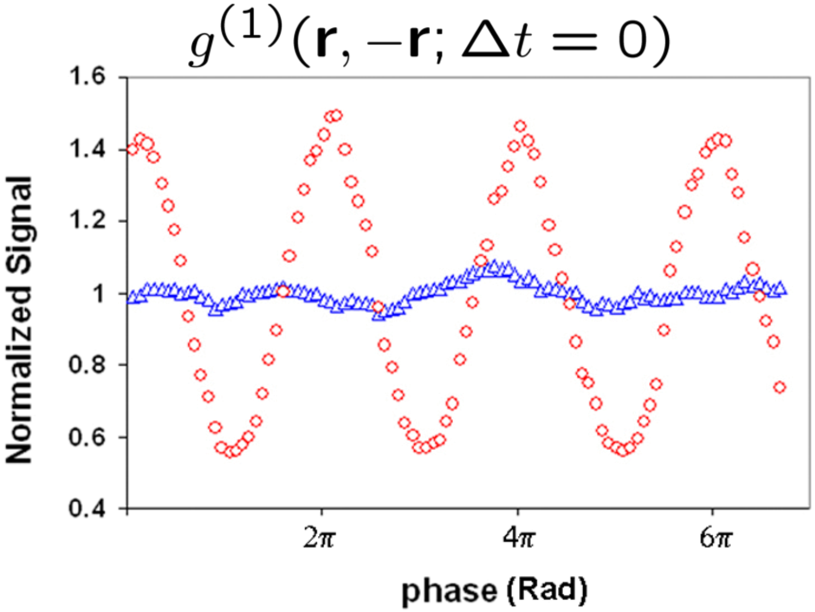
Stevenson *et al.* PRL **85** 3680 (2000)

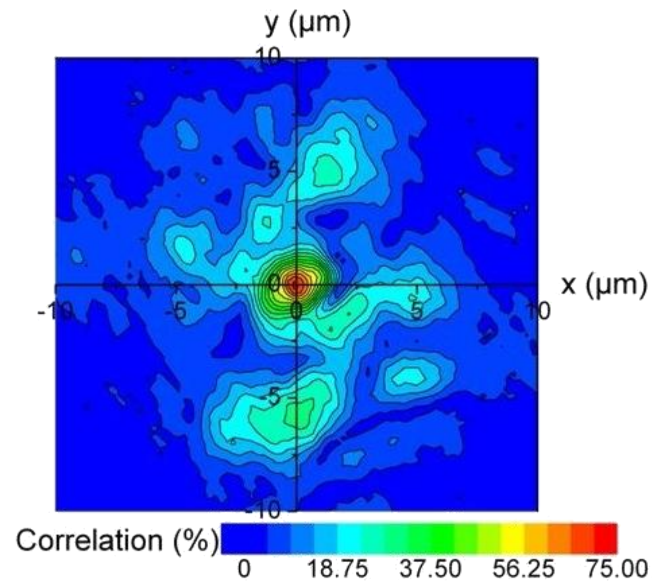
Evidences of Condensation in CdTe

Kasprzak et al., *Nature* **443**, 409 (2006)



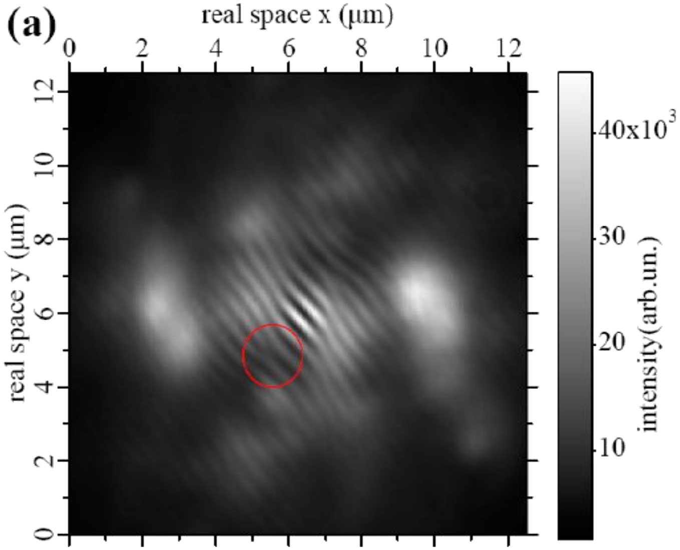




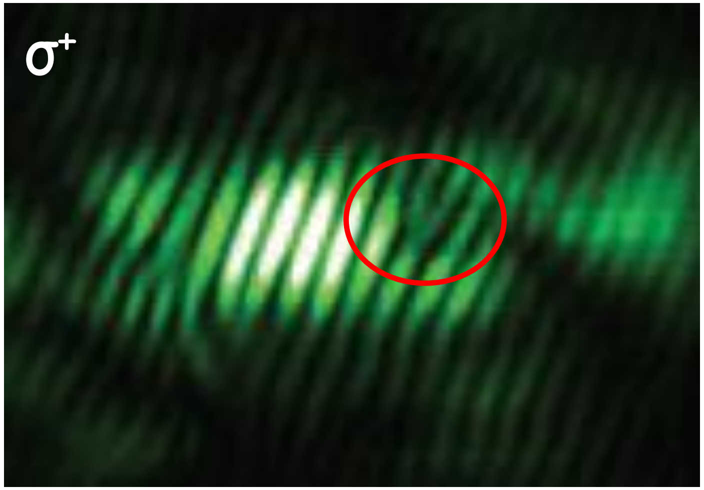


State of the Art

Vortices and half vortices

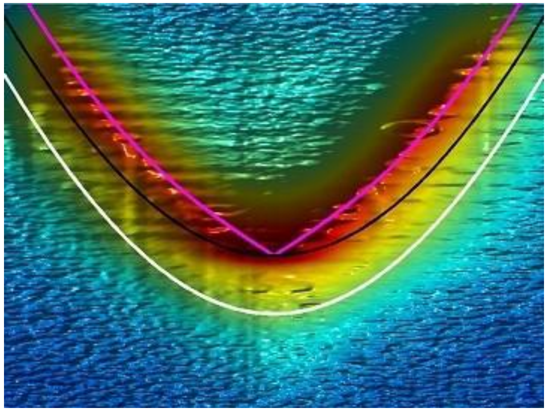


K. G. Lagoudakis et al, Nature Physics (2008)



Science 326, 974 (2009)

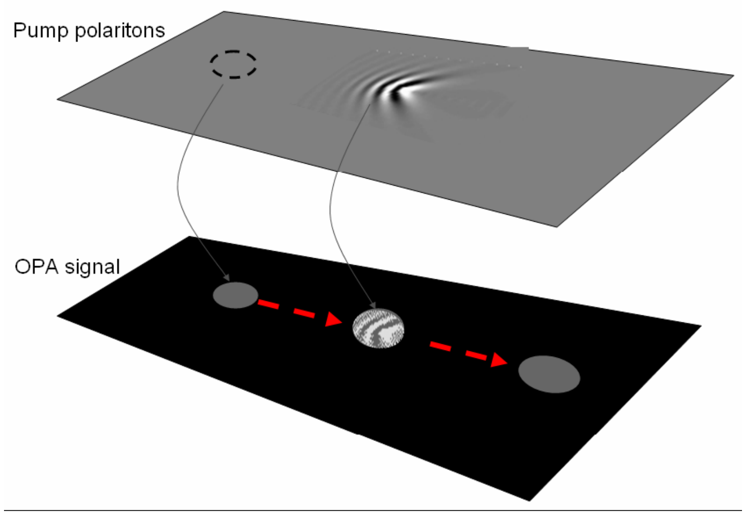
Bogoliubov Excitation Spectrum



S. Utsunomiya et al, Nature Physics (2008)

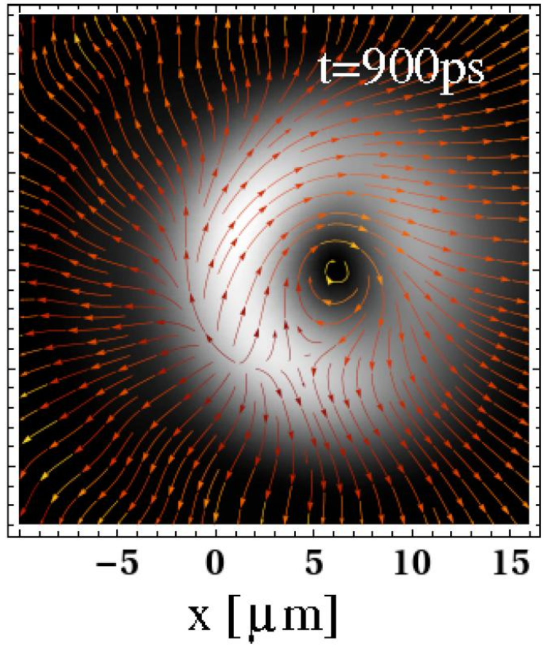
State of the Art

Flow via obstacle



Amo, Sanvitto, et al, *Nature* 2009

Persistent Quantised Currents



[Sanvitto, Marchetti, Szymanska *et al.*, *Nat. Phys.* 2010 arxiv/0907.2371]

GaN Polariton Lasing – room temperature effects

S. Christopoulos et al, *PRL* **98**, 126405 (2007)

Polaritons' Special Features

✓ 2D system but … finite size

✓ Internal polariton structure and strong interactions

- photonic component make polaritons easily overlap

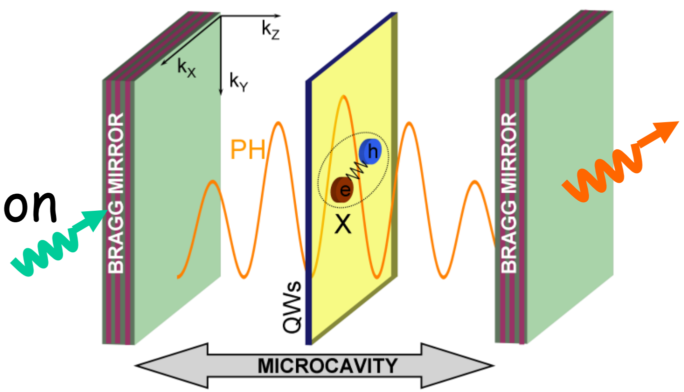
✓ Phase diagram – what is the most important?

- Kosterlitz-Thouless – interactions dominated?
- "finite size" BEC - confinement dominated?
- something else?

✓ Continues pump and decay

- non-equilibrium steady-state condensation

✓ Excitonic and Photonic disorder



The Phase Diagram

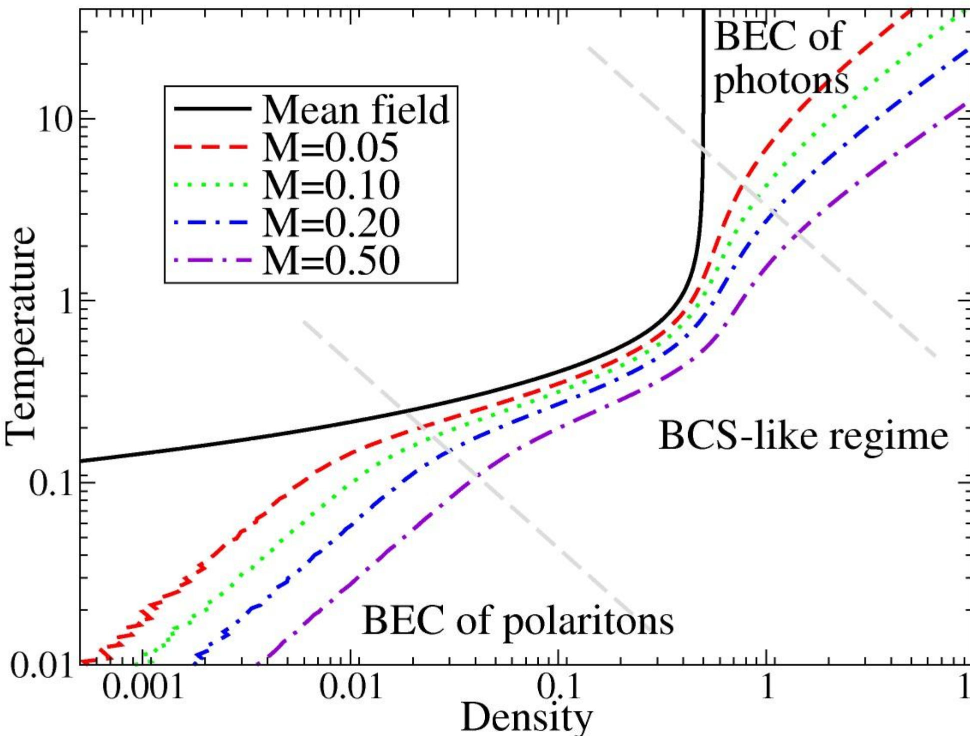
✓ Mean-field

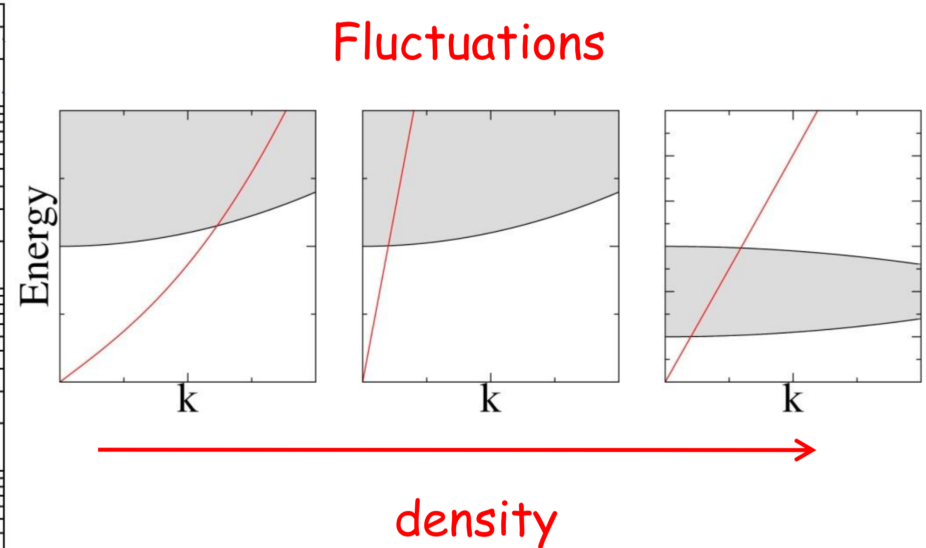
$$|\Psi\rangle = e^{\lambda(\psi_0^\dagger + \sum_\alpha X_\alpha b_\alpha^\dagger a_\alpha)} \prod_\alpha a_\alpha^\dagger |0\rangle = e^{\lambda\psi_0^\dagger} \prod_\alpha (v_\alpha b_\alpha^\dagger + u_\alpha a_\alpha^\dagger) |0\rangle$$

Two coupled order parameters

- Coherent photon field $\langle\psi\rangle$
- Exciton condensate $\sum_\alpha \langle a_\alpha^\dagger b_\alpha\rangle$

✓ Mean-field + fluctuations : BEC-BCS-BEC crossover with changing density



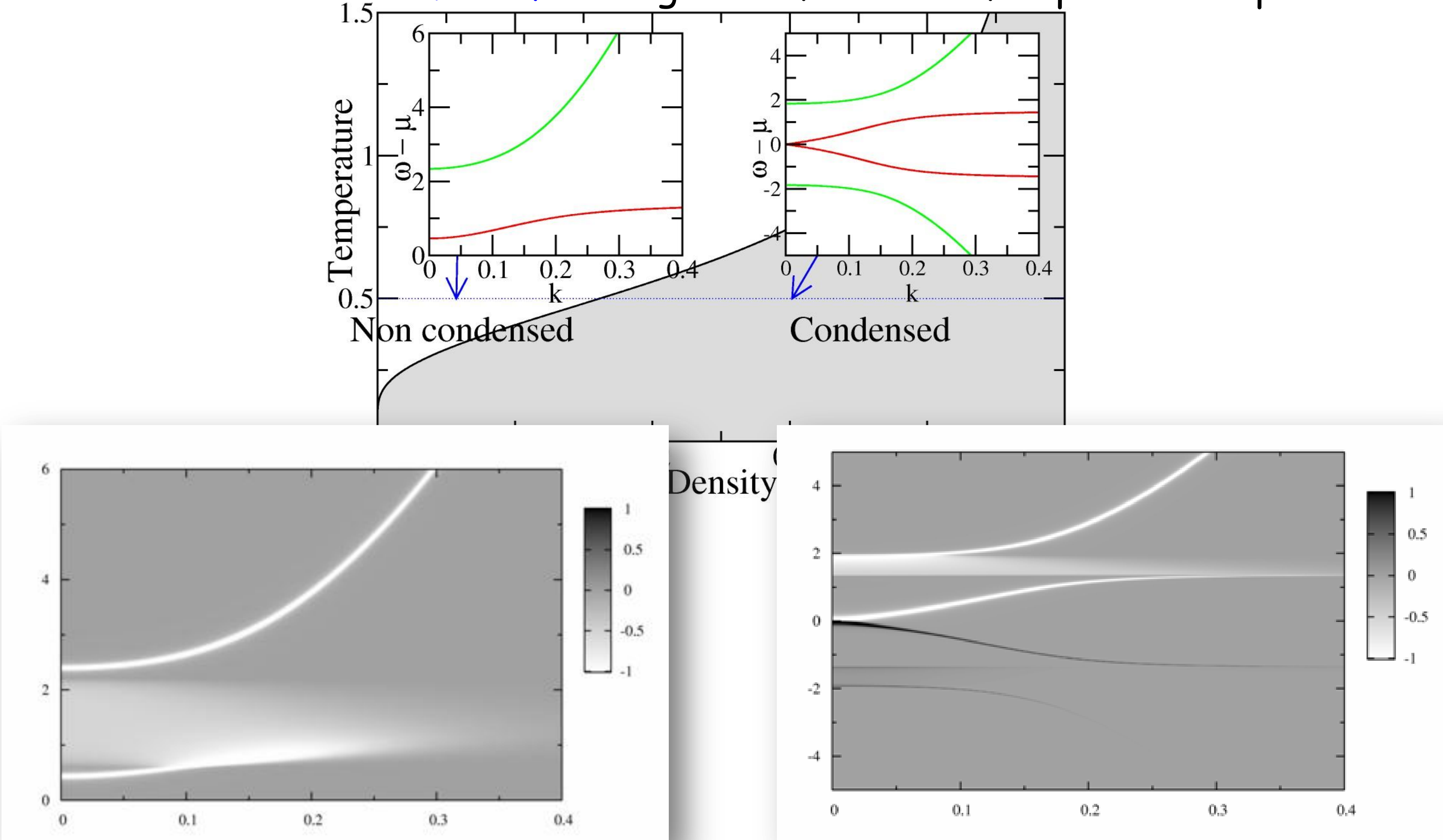


Keeling et al. *PRL* **93** 226403 (2004) PRB (2005)

Fluctuation Spectrum and Collective Modes

Keeling et al. *Phys. Rev. Lett.* **93**, 226403 (2004)

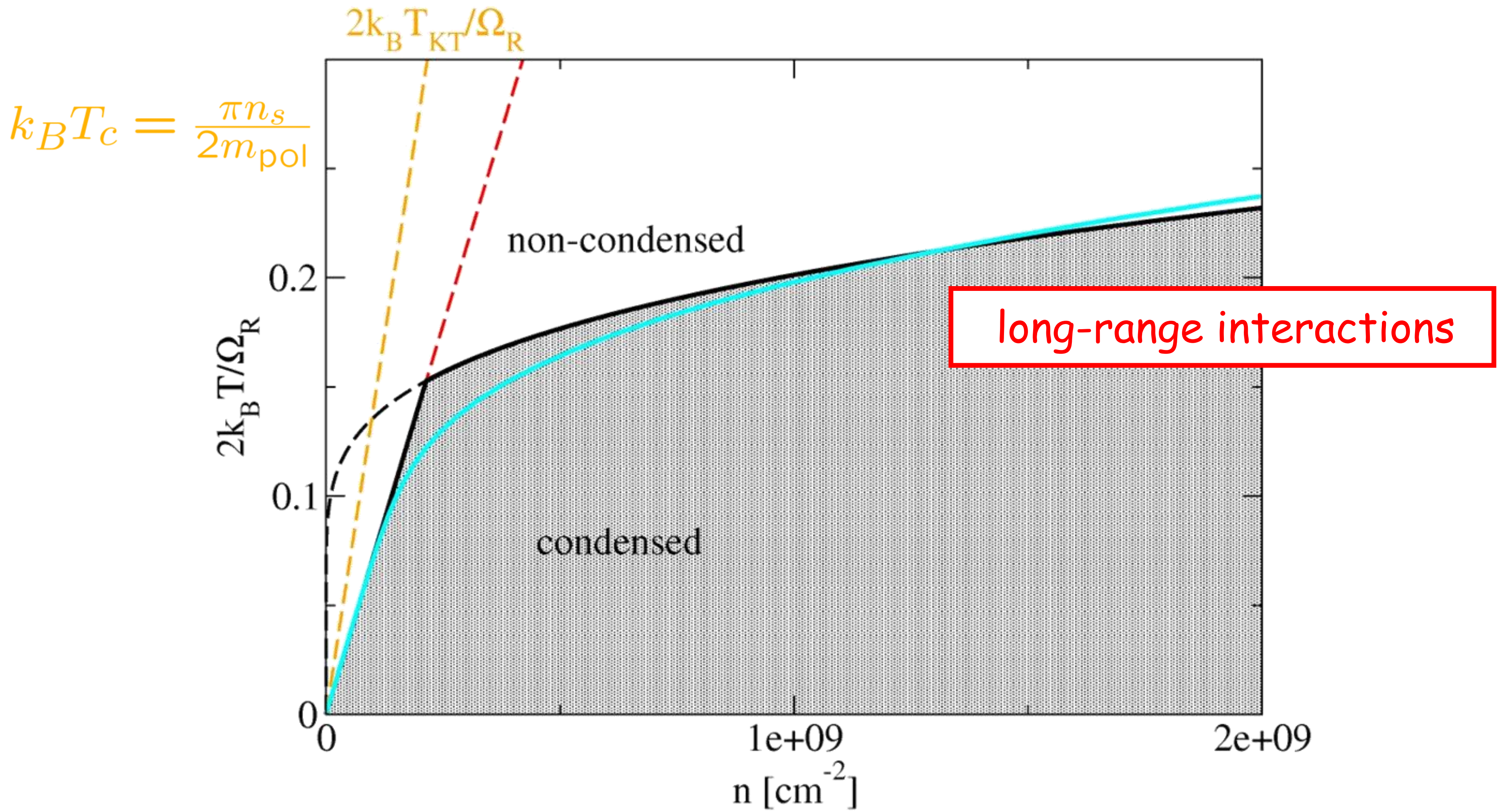
Fluctuations about mean field - greens functions for photon response



Uncondensed Spectra: polariton dispersion

Condensed Spectra: phase and amplitude modes

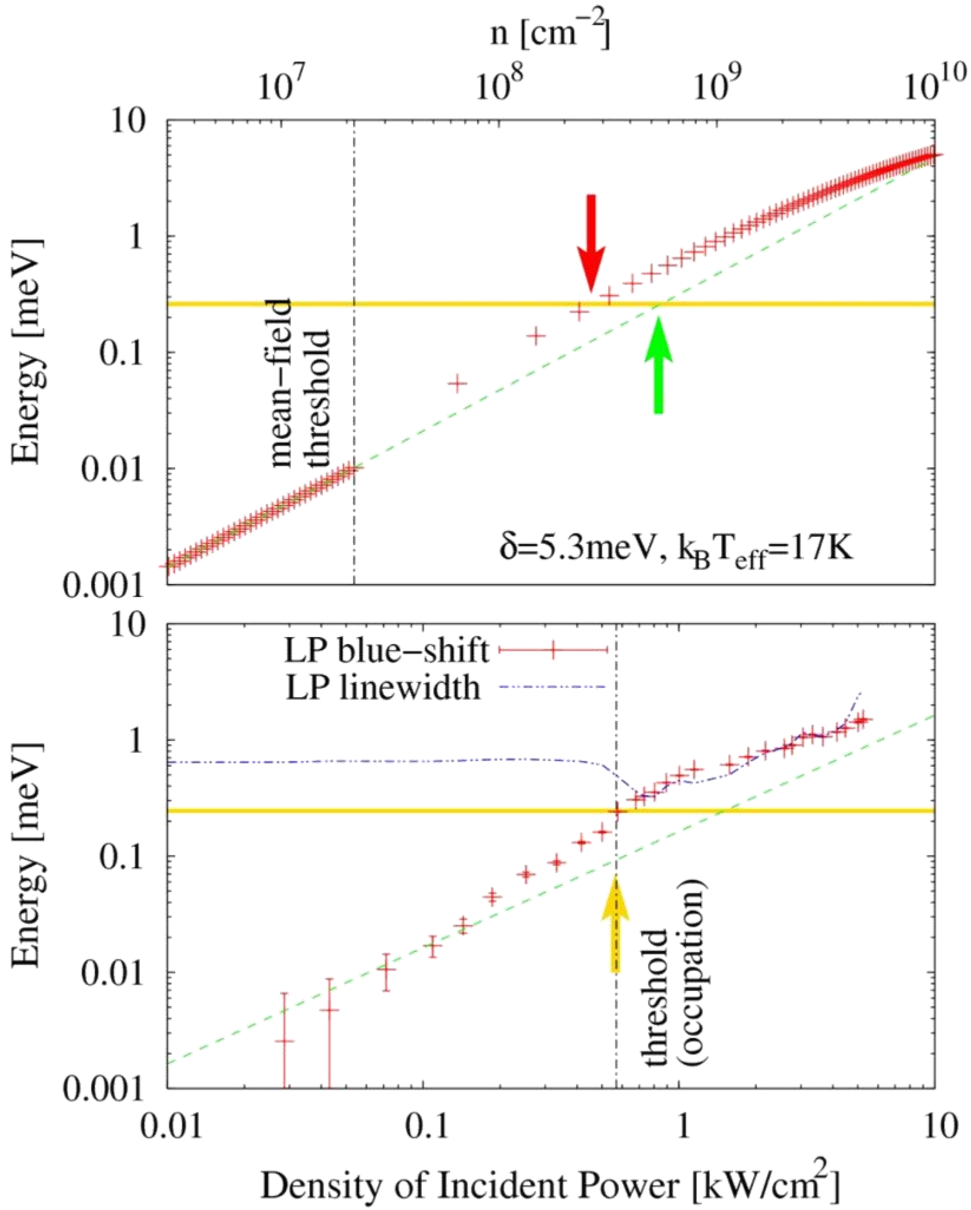
Beyond mean field: Interaction driven or dilute gas?



When $k_B T_c \sim \Omega_R$, deviations from BEC of structureless polaritons

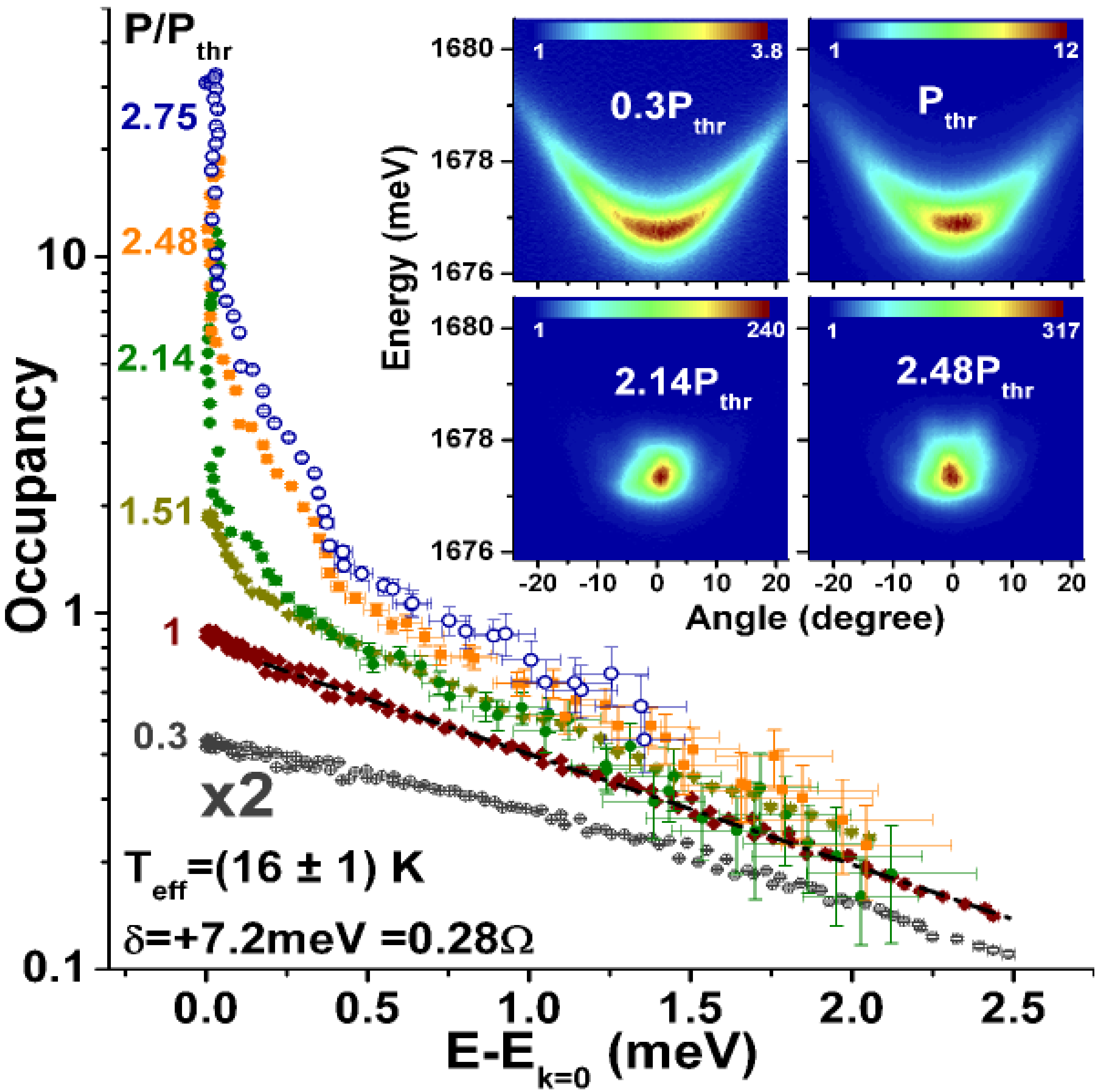
J. Keeling et al, *PRL* **93**, 226403 (2004)
F.M. Marchetti et al, *PRL* **96**, 066405 (2006)

How to Estimate Density?

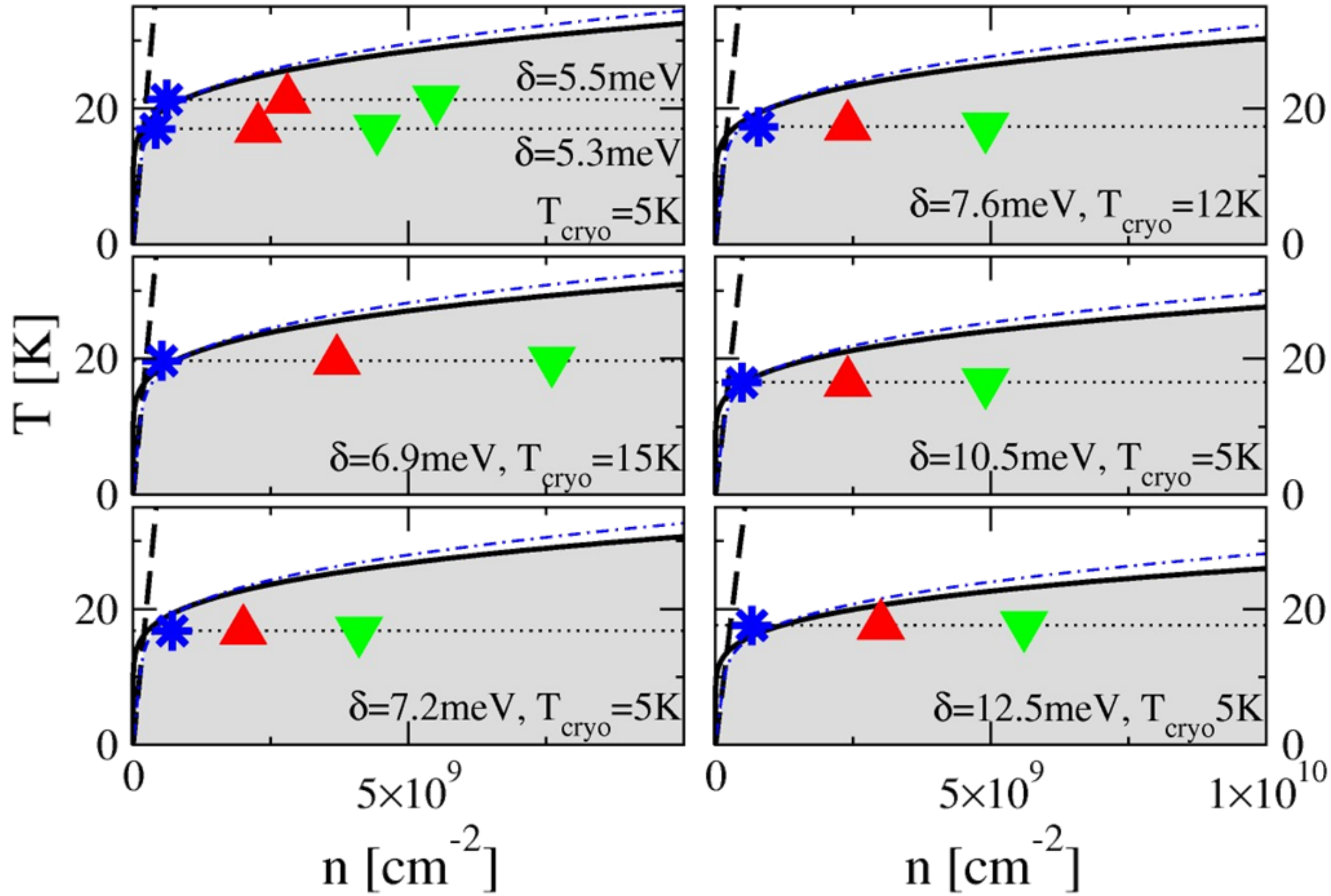


F.M. Marchetti et al, *Phys. Rev. B* **77**, 235313 (2008)

How to Estimate Temperature?



Data on the Phase Diagram



F.M. Marchetti et al, *Phys. Rev. B* **77**, 235313 (2008)

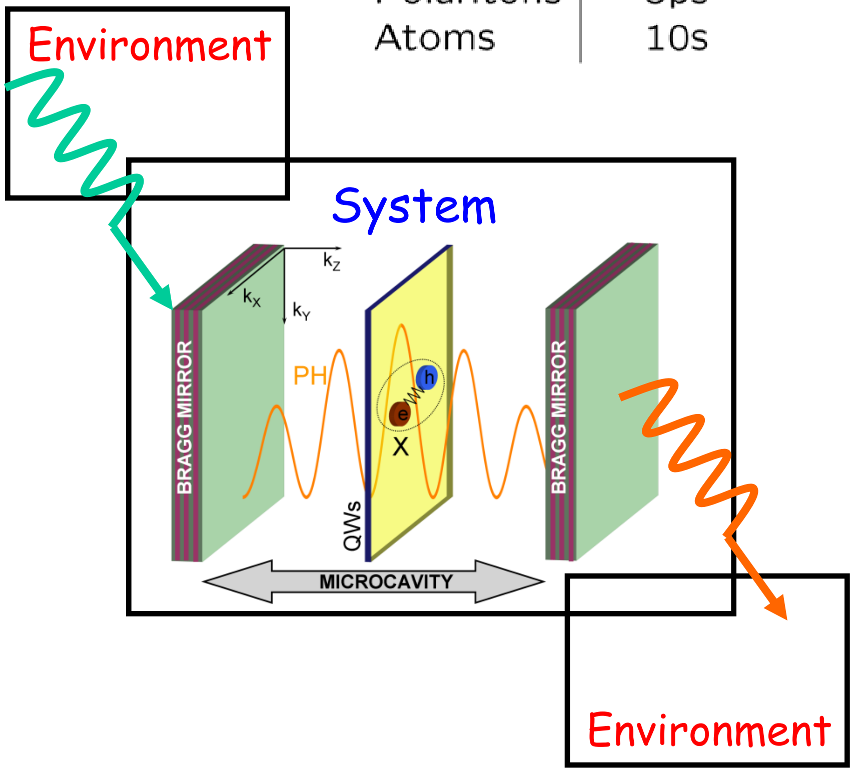
- ✓ Experiments on CdTe in the crossover between a fluctuation dominated WIBG and a mean-field-like collective state.
- ✓ Not easy to move away from this regime:

T polaritons different from T lattice

Condensation in Dissipative Systems

✓ Open systems in contact with environment

	Lifetime	Thermalisation	Linewidth	Temperature	
Polaritons	5ps	0.5ps	0.5meV	20K	2meV
Atoms	10s	1ms	2.5×10^{-13}meV	10^{-8}K	10^{-9}meV



Concepts: BEC in novel conditions, robustness to dephasing